
ARMY RESEARCH LABORATORY



Numerical Modeling of Buried Mine Explosions

by Gerald I. Kerley

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prepared by
Gerald I. Kerley
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Gerald I. Kerley

Weapons and Materials Research Directorate, ARL

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Contents

List of Figures	v
1. Introduction	1
2. Material Models	2
2.1 Dry Sand.....	2
2.2 Wet Sand.....	3
2.3 TNT Explosive.....	4
2.4 RHA Steel.....	4
2.5 Air.....	5
3. CTH Calculations	5
4. Conclusions and Recommendations	9
5. References	11
Distribution List	13
Report Documentation Page	19

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List of Figures

Figure 1. Hugoniot for sand, initial density 1.6 g/cc.	3
Figure 2. Hugoniots for wet and dry sand. Both curves were calculated from the models described in the text.	4
Figure 3. 2-D CTH calculations of a buried mine explosion in dry sand. Zone size was 1 cm.	6
Figure 4. Effect of zone size on vertical momentum of plate. Calculations are for a buried mine in dry sand. Results are shown for three zone sizes.	7
Figure 5. Effect of geometry on vertical momentum of plate. Calculations are for a buried mine in dry sand. Zone size was 3 cm in both 3-D and 2-D calculations.	8
Figure 6. Effect of soil type on vertical momentum of plate. Calculations were 2-D, with zone size of 2 cm.	9

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1. Introduction

Numerical simulation of the effects of buried mine explosions on armored vehicles is a topic of considerable interest to the U.S. Army Research Laboratory (ARL). Recent CTH hydrocode calculations by ARL personnel are discussed in the literature [1, 2]. It has been discovered that a lack of good equations of state (EOS) for various soil types is a major cause of uncertainty in the calculated results.

The present work was commissioned to support ARL personnel in their studies of this problem. One of the immediate needs of the ARL program is to simulate experiments that will be carried out at the Vertical Impulse Measurement Facility (VIMF) under development at ARL. VIMF will measure the loading of a steel plate suspended over mines exploded in various types of soil. The vertical momentum imparted to the plate is a quantity of particular interest, along with the plate distortion and rotation.

The present study was preliminary and exploratory. The principal goals included the following.

- Assist in setting up CTH input files [3–7] for simulating a VIMF test.
- Develop preliminary EOS models for soil types of interest.
- Make sensitivity studies of the CTH predictions to various aspects of the model.
- Make recommendations for follow-on work, where appropriate.

In Section 2, the material models used in the calculations are discussed. After some study of the existing models, we decided to use a recently-developed EOS table for fused quartz [8], together with the palpa porosity model [6, 7], to model dry sand. This table, existing models for water, and the PANDA code [9] were also used to construct a new EOS table for wet sand.

In Section 3, CTH calculations of a buried mine explosion using the new EOS models are discussed. Calculations were made in both two and three spatial dimensions for varying zone sizes, and for both dry and wet sand. A mine buried in wet sand is much more lethal than one in buried dry sand; wet sand produced three times as much vertical plate momentum as dry sand. This result disagrees with previous calculations made with other soil models.

The results of this work should be regarded as preliminary. Recommendations for additional studies are given in Section 4.

2. Material Models

In this section, we describe the equations of state and other constitutive model parameters used for the materials in this study—dry sand, wet sand, TNT, RHA steel, and air.

2.1 Dry Sand

Sand is a porous aggregate of particles of various minerals, most commonly silica (fused quartz). The properties of sand can vary, depending on the degree of compaction, the minerals present, and the moisture content. In this study, fused quartz is assumed to be the only mineral present. A typical density for quartz sand is about 1.6g/cc; that corresponds to a porosity of 27.4%, assuming an initial density of 2.2g/cc for solid silica.

The p-alpha model, together with a tabular EOS for the solid, or “matrix” material is used to model sand. Two EOS tables for the matrix material were considered—one available in the standard CTH database (EOS no. 7100 on file “seslan” [10]), and a new EOS for fused quartz, which was recently developed for another application [8].

Figure 1 compares Hugoniots for the two EOS tables with experimental data [11] for quartz sand; the initial densities were in the range 1.58–1.65 g/cc. Our new fused quartz EOS (no. 7010) gives good agreement with the data; it gives the correct density at low pressures and reproduces the phase transition in the pressure range. The seslan table gives only fair agreement that is not as good as our new EOS table.

Another problem with the seslan table is that it does not include the Maxwell constructions that are necessary to model vaporization behavior. CTH calculations using this table exhibited time step problems, evidently due to problems in the tension/vaporization region, and would not run to completion. Most (but not all) of these problems were eliminated when we modified the table to include the Maxwell constructions. In this report, the calculations using the seslan table are not discussed.

The p-alpha model was used to treat the porosity. The initial density was taken to be 1.6 g/cc. We used the default crush pressure ($PS = 1.0E9$ dynes/cm 2) and did not include an elastic crush region. It may be desirable to improve upon this aspect of the model in future work; however, the details of the crushing behavior are of secondary importance in predicting the loading of the steel plate (see Section 3).

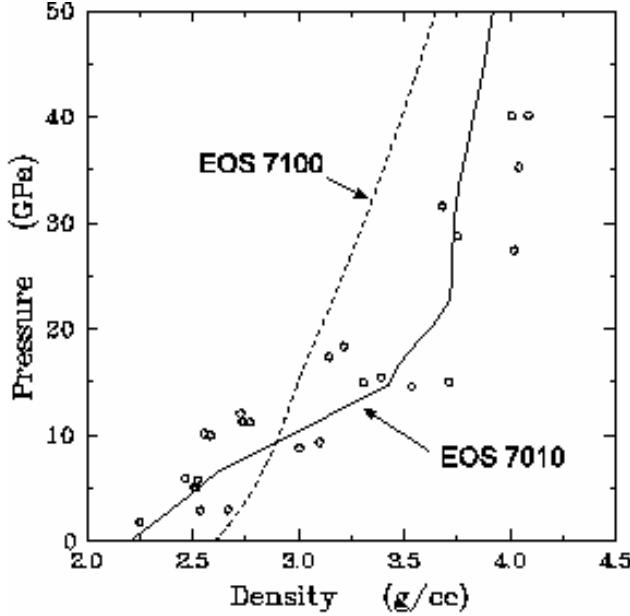


Figure 1. Hugoniot for sand, initial density 1.6 g/cc. Circles represent experimental data from van Thiel [11]; solid curve represents new EOS table no. 7010 for fused quartz; dashed curve represents seslan EOS table no. 7100 for sand.

Because sand is so porous, it is not expected to support much elastic deformation or tension. Therefore, we used only nominal values for the material strength and fracture parameter—the elastic perfectly plastic model with a yield strength of 1.0E9 dynes/cm² and Poisson’s ratio of 0.3, and a fracture strength of -1.0E6 dynes/cm². Here again, these features of the model can be improved in future work, but are of secondary importance now.

2.2 Wet Sand

For a porosity of 27.4%, fully-saturated wet sand would have a composition of 85.5% silica/14.5% water by weight and a density of 1.87 g/cc. We constructed an EOS table for this composition using the PANDA mixture model [9]. The procedure was similar to that used for dry sand (fused quartz), except that water and hydrogen were added. Hence, the calculations included the following species: fused quartz, liquid quartz, stishovite, water, liquid silicon, molecular and atomic oxygen, and molecular and atomic hydrogen.

Figure 2 compares the calculated Hugoniot for wet sand (EOS table no. 7011) with that for dry sand (EOS table no. 7010). While the Hugoniots for the two materials are not very different in the pressure-density plane, the porosity of dry sand has a significant effect on the Hugoniot energy. As shown in Figure 2, the energy of dry sand is 50–100% greater than for wet sand at the same shock pressure. For this reason, dry sand is able to absorb more of the explosive energy

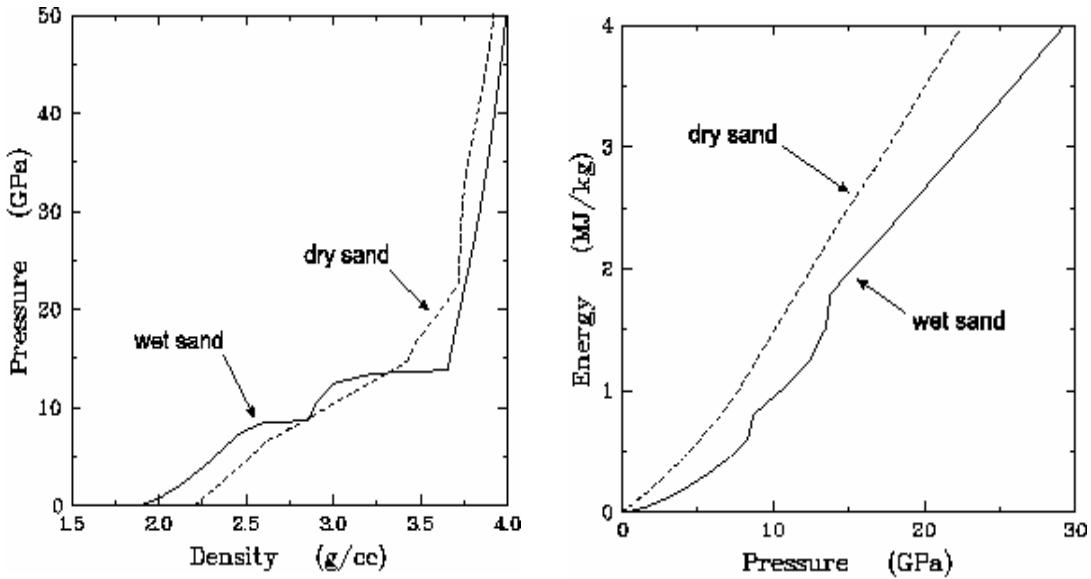


Figure 2. Hugoniots for wet and dry sand. Both curves were calculated from the models described in the text.

than wet sand in a buried mine explosion. As we will show in Section 3, an explosion in dry sand produces less acceleration of the steel plate than an explosion in wet sand.

Because of its water content, wet sand is not expected to support significant elastic deformation or tension. Therefore, the yield strength was set to zero. Since the EOS does not have a tension region, except at very low temperatures, we have not allowed it to fracture. The p-alpha model was not used because the material is not porous.

2.3 TNT Explosive

The explosive was modeled using the default JWL EOS for TNT. It was detonated by programmed burn at the bottom center, with a detonation velocity of 6.93E5 cm/s [12].

2.4 RHA Steel

The default SESAME tabular EOS was used for RHA steel. As shown by Kerley [13], this EOS treats the polymorphic and melting transitions in iron, and it gives very good agreement with shock wave and penetration experiments. We also used the same material strength and fracture parameters as Kerley [13]—the elastic-perfectly plastic model with a yield strength of 1.5E10 dynes/cm² and Poisson's ratio of 0.285, and the Johnson-Cook fracture model with a fracture strength of -3.8E10 dynes/cm².

2.5 Air

The default SESAME tabular EOS [6] was used for air.

3. CTH Calculations

To test the model and examine trends, both two-dimensional (2-D) and three-dimensional (3-D) versions of the following problem were considered.

- The explosive was modeled as a disk of TNT, 30 cm in diameter and 8 cm in thickness, with no case. The initial explosive density was 1.63g/cc, giving a total explosive weight of 9217g (20.32 lb).
- The top of the explosive charge was 16 cm (6.3 in) from the soil surface.
- The RHA steel plate was 46 cm (18 in) from the soil surface.
- In the 3-D problem, the center of the plate was offset 61 cm (24 in) from the center of the explosive charge. In the 2-D problem, the plate was positioned directly over the explosive.
- In the 3-D problem, the plate was 244 cm (8 ft) square and 20 cm (8 in) thick. In the 2-D problem, the plate was a disk, 276 cm (9 ft) in diameter and 20 cm thick, giving the same mass as in the 3-D problem.

Calculations were carried out with the February 99 version of CTH, except that a more recent version of routine SESESX was used. The modified routine had corrections to the p-alpha model, and so it could have some effect on the calculations reported here. (The modified routine has been provided to ARL.)

Figure 3 shows snapshots of a 2-D calculation in dry sand six times from 0 to 2 ms. The thickness of the sand layer between the explosive and the plate drops markedly as the porosity is crushed out and the explosive products expand. Only a thin layer of sand actually impacts the plate. For this reason, we believe that the explosive gases, not the sand, deliver most of the impulse to the plate. If so, the results should not be very sensitive to the properties of the thin sand layer. Therefore, details of the porosity crushing and fracture should be of secondary importance to the predictions.

By contrast, the initial porosity of the sand is very important. As shown in Figure 2, porosity increases the Hugoniot energy at a given shock pressure, so that more porous soils will absorb more of the explosive energy. Note that the composition of the soil below the explosive will also have an important effect on impulse delivered to the plate. A rock layer, or even a wet sand layer, underneath the charge will reflect more of the explosive energy upward, giving a greater impulse.

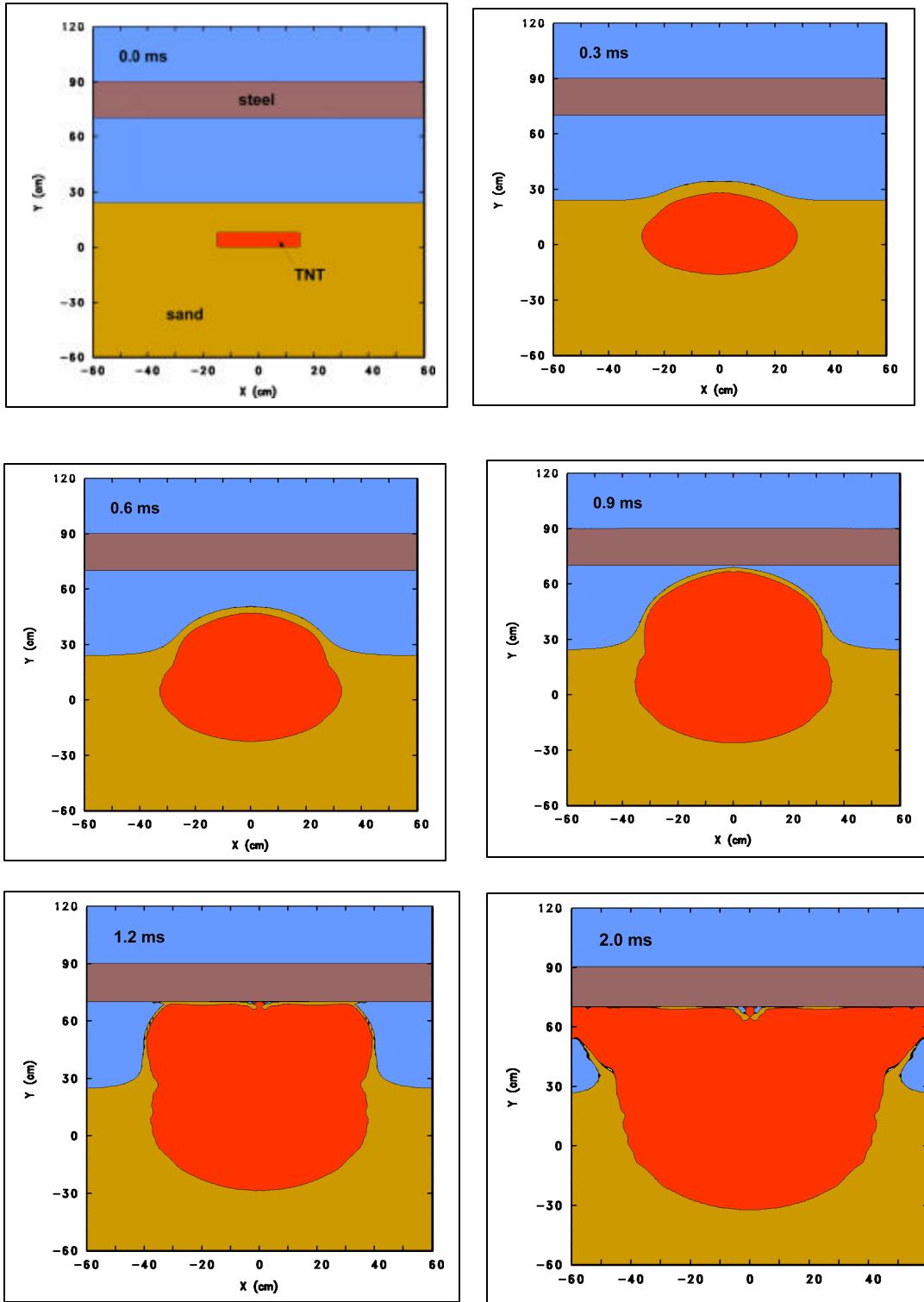


Figure 3. 2-D CTH calculations of a buried mine explosion in dry sand. Zone size was 1 cm.

In the calculations for wet sand, the soil layer does not thin down as it does in dry sand. One reason for this fact is that wet sand is not porous and therefore does not compress as much as dry sand when shocked. In that case, the sand makes a larger contribution to the impulse delivered to the plate.

Figure 4 shows the vertical momentum delivered to the plate as a function of time for a calculation in dry sand. The predictions are compared for three different zone sizes—1, 2, and 3 cm. The results show that the very coarse zoning gives reasonable results at late times. The results at early times are most sensitive to the zone size.

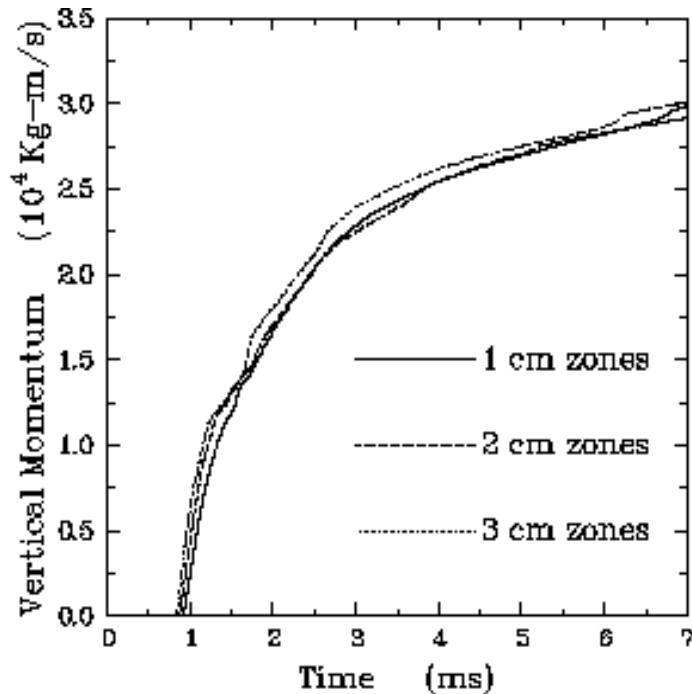


Figure 4. Effect of zone size on vertical momentum of plate. Calculations are for a buried mine in dry sand. Results are shown for three zone sizes.

Figure 5 compares the predictions for 2-D and 3-D calculations in dry sand.* The same zone size, 3 cm, was used in both cases. The results show that the 2-D model is satisfactory for predicting the vertical momentum. Of course, 3-D effects would be more important for other quantities, especially those involving the rotational motion of the plate.

* The 3-D calculation used an axis of symmetry at $z = 0$, y being the vertical direction, so only half of the plate was actually included in the calculation. The momentum calculated by the code had to be multiplied by a factor of two to account for the full mass of the plate.

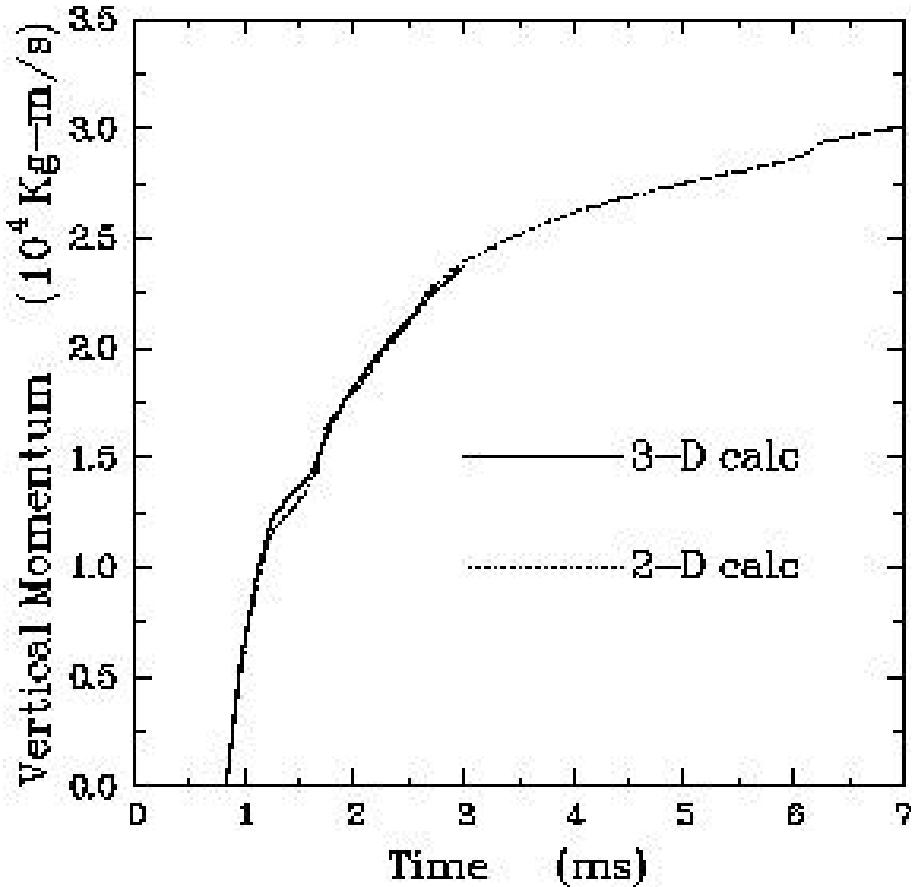


Figure 5. Effect of geometry on vertical momentum of plate. Calculations are for a buried mine in dry sand. Zone size was 3 cm in both 3-D and 2-D calculations.

Finally, Figure 6 compares the vertical momentum of the plate for dry and wet sand. Both calculations were made in 2-D geometry, with a zone size of 2 cm. The momentum for an explosion in wet sand is roughly three times higher than it is for dry sand. This difference is surprising because it is so much higher than has been predicted in earlier calculations with other soil models [1, 2]. It can be attributed, at least in part, to the following two factors.

- (1) As shown in Figure 2, the porous dry sand can absorb roughly twice as much energy of the explosive charge as the nonporous wet sand.
- (2) The sand layer in front of the expanding explosive reaction products is thicker for wet sand than it is for the porous dry sand, which compresses so much more once it is shocked. However, this result should be regarded as preliminary until additional studies are made.

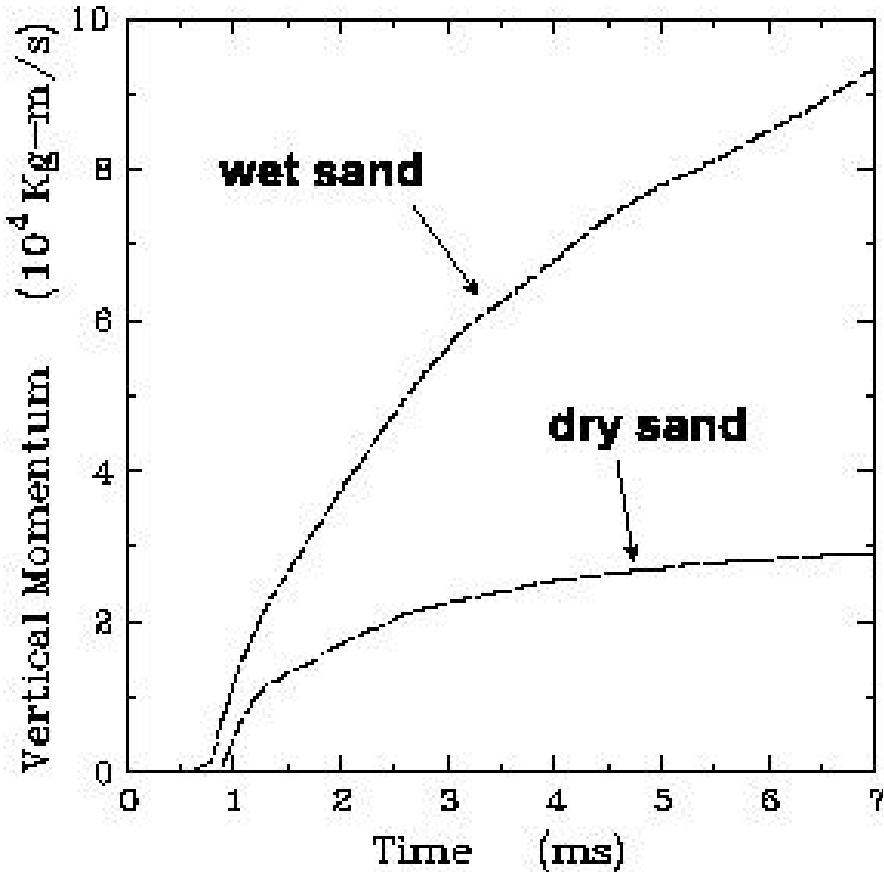


Figure 6. Effect of soil type on vertical momentum of plate. Calculations were 2-D, with zone size of 2 cm.

4. Conclusions and Recommendations

We constructed new EOS tables for dry and wet sand and then used these tables in calculations of buried mine explosions. Calculations were made of the vertical momentum imparted to a steel plate positioned over the exploding mine. It was shown that 2-D and 3-D versions of the problem give quite similar results for the vertical momentum.

The calculations for wet and dry sand gave dramatically different results. The vertical momentum for the wet sand was about three times larger than it was for dry sand—a much greater difference than has been observed in previous calculations [1, 2]. These results are preliminary, and further studies are needed to confirm them.

The following matters should be investigated in future work.

- (1) The sand models should be tested further and improved, if needed.

- (2) The densities and water contents of the soil samples should be checked against those to be used in the experiments and revised, if necessary.
- (3) Sensitivity studies should be made to identify what other factors in the numerical model are most important and where further improvements are needed.
- (4) EOS tables for additional soil types (e.g., dry and wet clay) should be constructed.
- (5) Further studies of the explosive model should be made—sensitivity tests to the detonation products EOS, an analysis of the effects of secondary reactions with air, and analysis of the effects of the case.
- (6) Comparisons with VIMF test data will also indicate areas where the modeling needs improvement.

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19

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